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STUDY OF ION-IMPLANTED SILICON SURFACE USING ACOUSTO-ELECTRIC VOLTAGE

by

M. E. Motamedi and P. Das

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Surface acoustic wave delay lines with semiconductor on $LiNbO_3$ structure were used for the study of surface potential barriers of ion implanted silicon samples. To achieve the same preparation condition and the same surface treatment, two ion implanted silicon samples were made from a 10 ohm-cm N-type silicon wafer with a (100) surface orientation. Boron ions were implanted to different depths, 1200 A° and 3200 A° for these two samples. A 10 ohm-cm N-type silicon with a high quality surface was also prepared for comparison and reference. Acousto-electric voltage with acoustic power of variable input

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STUDY OF ION IMPLANTED SILICON SURFACE USING ACOUSTOELECTRIC VOLTAGE*

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ABSTRACT. Surface acoustic wave delay lines with semiconductor on $LiNbO_3$ structure were used for the study of surface potential barriers of ion implanted silicon samples. To achieve the same preparation condition and the same surface treatment, two ion implanted silicon samples were made from a 10 ohm-cm N-type silicon wafer with a (100) surface orientation. Boron ions were implanted to different depths, 1200 A^o and 3200 A^o for these two samples. A 10 ohm-cm N-type silicon with a high quality surface was also prepared for comparison and reference. Acoustoelectric voltage with acoustic power of variable input was investigated for surface study of these three samples. For those samples which are implanted, the results show a large change in transverse acoustoelectric voltage. Using light of variable intensity to illuminate the surface of the sample through the $LiNbO_3$, we can obtain a qualitative measure of the surface state density and charge carrier density at the surface. It is also found that the inversion layer produced by implantation moves toward the surface as the light intensity increases.

Introduction

Surface Acoustic Wave (SAW) devices have been used recently for the study of semiconductor surface.[1-8] In this technique, the surface of semiconductor under test is placed near to the surface of a piezoelectric substrate separated by a uniform air gap. The nonlinear coupling of semiconductor surface-charge carriers with the piezoelectric field accompanied with the SAW propagating on the surface of substrate gives rise to an acoustoelectric effect. As a result of this interaction, a nonlinear drift current will flow in the semiconductor proportional to the product of electric field associated with the SAW and perturbed carriers. This product contains the second harmonic generation and a dc term. The dc term is the source of acoustoelectric voltage which can be detected through a low-pass filter and has two components: one longitudinal in the direction of propagation and the other transverse, normal to the surface.

A proper device for measurement has usually three terminals: terminals "1" and "2" are connected to the transducers of the SAW delay line and terminal "3" is connected to the back side of the semiconductor surface. If both terminals "1" and "2" are fed with a rf pulse, terminal "3" demonstrates the convolution. When terminal "1" is fed with a rf pulse, terminal "2" shows the variation of delay line attenuation, α, and terminal "3" through a low-pass filter shows the normal component of acoustoelectric voltage, V_{ac}. Because of this acoustoelectric coupling, the SAW propagating on the surface of piezoelectric substrate will suffer more attenuation and the delayed rf signal from terminal "2" has an amplitude variation related to the semiconductor surface properties.

Due to the nonlinear interaction of the charge carriers near the semiconductor surface with the electric field associated with the SAW, both delay line attenuation and acoustoelectric voltage are a function of the initial condition of semiconductor surface potential u_s prior to the interaction to the SAW. In the absence of surface states the surface potential u_s equals the bulk potential u_B in the semiconductor substrate.

However, the presence of surface states will bend the energy band in the semiconductor, resulting in a non-zero value of the surface bending potential, $U_s = u_s - u_B$, which can be positive or negative dependent on the type of surface traps. When U_s is positive for an N-type sample, the surface charges are accumulated and when U_s is negative, the semiconductor surface is either depleted or inverted. The resulting attenuation α and acoustoelectric V_{ac}, are a function of the amount of bending potential U_s. Light incident on the semiconductor surface can be used to vary U_s, since the incident intensity will change the charge carrier density at the surface (and hence U_s) by band to band carrier generation as well as by filling surface traps. The time dependence of attenuation and acoustoeletric voltage is a measure of the lifetime of surface state traps located in that part of the energy band gap of the semiconductor being swept by that particular u_s.

Both acoustoelectric voltage[3,4] and variation of attenuation α[1,5] are used for the study of semiconductor surfaces. When the variation of attenuation is used, the terminal "3" of the device is free and it can be used to apply a dc electric field normal to the semiconductor surface to change the surface bending potential and bias the initial surface condition to accumulation, depletion or inversion at will.

When V_{ac} is used for surface study the shift in surface potential is done only by application of an intense light. Since V_{ac} is a capacitive-coupled potential from the piezoelectric field, it is a transient signal and the steady-state of the waveform has a zero voltage level.

In this paper we will devote most of our attention to the study of V_{ac} variation and relate that to surface potential of silicon wafers which have ion implanted layers in the vicinity of the surface. The presence of an implanted ion distribution near the surface has the effect of changing the shape of U_s as a function of depth into the semiconductor. Thus, the location of implant and the shape of its distribution relative to the value of the effective Debye length corresponding to the doping distribution, will determine the degree of SAW interaction with the charge carriers and hence, the acoustoelectric voltage.

Experiment

The experimental arrangement is shown in Fig. 1. $LiNbO_3$(Y-Z) is used as a piezoelectric substrate. Terminals "1" and "2" are two identical 112 MHz interdigital transducers which can be used to generate a SAW propagating on the highly polished surface of the

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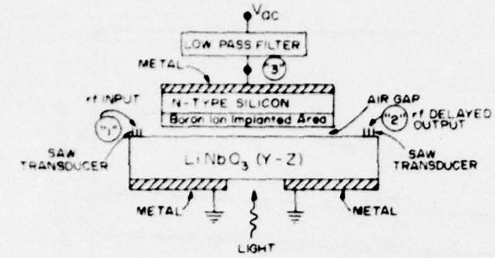

Fig. 1 Experimental configuration for SAW interaction with semiconductor surface

$LiNbO_3$ substrate. Terminal "1" is fed by a 112 MHz rf pulse of variable duration and a rise time of less than 10 nanoseconds. Propagating SAW will pass under the implanted surface of silicon sample, separated by a uniform air gap from the surface of $LiNbO_3$. An imaging technique is used to electronically reveal a uniform pressure along the sample. A light source was used to illuminate the silicon sample through the $LiNbO_3$ by providing an opening in the back metal contact of $LiNbO_3$.

Normal component of acoustoelectric voltage V_{ac}, can be detected from terminal "3" through a low-pass filter. Typical waveform for V_{ac}, when the rf pulse duration is relatively long, is shown in Fig. 2. It

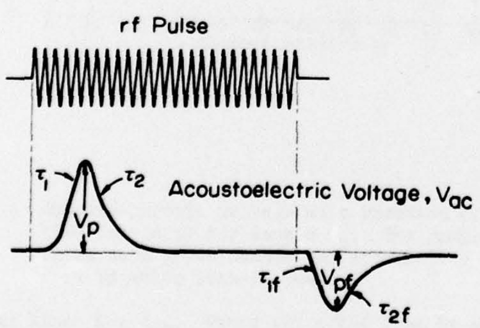

Fig. 2 Typical trace of acoustoelectric voltage for N-type silicon samples with fixed light intensity to define the parameters of interest. The initial peak voltage is V_p. The subscript f will be added to denote parameters associated with the final edge of the rf pulse.

was indicated that V_{ac} is a capacitive coupled potential. The main capacitors for this coupling are: C_D, depletion capacitance; C_G, gap capacitance; C_B, bulk capacitance across the Debye length; and C_L, the capacitance of $LiNbO_3$.

The three capacitors C_G, C_D and C_B are in series with R_B, bulk resistance of the sample, and they represent the source impedance of the V_{ac}, assuming the surface potential has not inverted the active surface.

The acoustoelectric voltage V_{ac} is a result of perturbation of the surface potential by SAW propagation which mainly consists of a nonlinear part u'_s, therefore, the surface bending potential will change to $U_s' = U_s + u'_s$. Since the nonlinearity of this coupling is much stronger for a semiconductor with charge carriers at the surface depleted, therefore, for an N-type semiconductor u'_s is positive.

When the semiconductor has a high quality surface without any surface states and any external applied field, the surface potential u_s is equal to the bulk potential u_B resulting in a zero bending potential $U_s = u_s - u_B = 0$ (flat band condition). In practice, the surface states are always present and U_s has a nonzero value and it can be either positive or negative depending on the kind of surface traps.

To explain the shape of acoustoelectric voltage shown in Fig. 2, consider an N-type semiconductor with a moderate density of surface traps and some value of $U_s \neq 0$. When SAW passes under the semiconductor the V_{ac} rises to V_p where the N-type surface is depleted resulting in a storage of positive charges at the surface. These charges are captured by surface traps and screen out a portion of peak acoustoelectric voltage V_p during the time constant τ_2 and until acoustic pulse exists under the semiconductor. When the acoustic pulse terminates, the resulting output potential reverses to $-V_{pf}$ and decays to zero by time constant τ_{2f}. The decay time τ_{2f} is the result of discharging the terminal capacitance and relaxation time of surface traps.

The difference $V_p - V_{pf} = V_d$ is the portion of V_p which is screened out by traps and consequently, is a measure of density of surface traps. When the surface of semiconductor containing surface traps is illuminated by a moderate light intensity, the surface traps are filled out and V_{pf} increases to the value V_p and V_d becomes zero. The same result ($V_p = V_{pf}$) can be observed of a semiconductor with a high quality surface at dark.

Three samples S_1, S_2 and S_3 were used in the experiment. S_1 is a 10 ohm-cm N-type silicon wafer with a (100) surface orientation and high polish surface. The surface damage had been reduced by growing 2000 A° SiO_2 in a dry O_2 ambient and then removing the oxide. S_2 and S_3 were similar substrates, but had been implanted with boron ions to different depth and subsequently heated at high temperature to activate the boron atoms as well as to anneal the damage to the surface caused by the implantation. In S_2 and S_3 the implant distributions were centered at 1200 A° and 3200 A° respectively. In both cases the standard deviation of the implant distribution was about 840 A° and the implant ion dose was $2.5 \times 10^{10}/cm^2$.

Results

Acoustoelectric voltage was observed as a function of incident light intensity and the data of both peaks V_p and V_{pf} were taken on each of the three samples. In all experiments, the input rf pulse was 15 volts peak-to-peak corresponding to zero dB. Results are plotted in Figs. 3, 4 and 5, for samples S_1, S_2 and S_3 respectively. In these plots, the ordinates in mv are peaks of acoustoelectric voltage; solid lines for V_p and

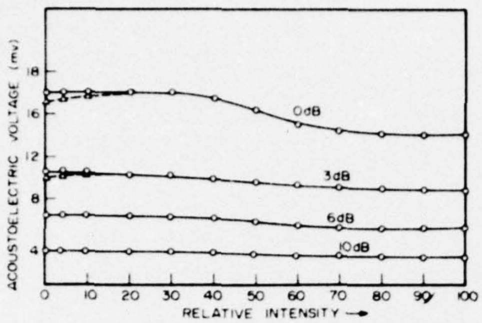

Fig. 3 Acoustoelectric voltage as a function of relative intensity for sample S_1. Where the solid line is only shown indicates that the dashed line is coincident on the solid line. The numbers in dB in each curve denote the attenuation of rf from 15 volts peak-to-peak.

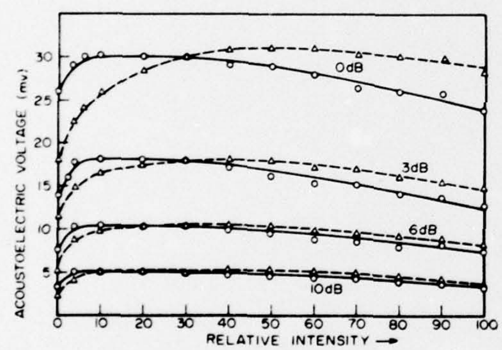

Fig. 4 Acoustoelectric voltage as a function of relative intensity for sample S_2. The numbers in dB in each curve denote the attenuation of rf from 15 volts peak-to-peak.

dashed lines for V_{pf}. Where the solid line is only shown, indicates that the dashed line is coincident on the solid line. The numbers in dB in each curve denote the attenuation of rf pulse input from 15 volts peak-to-peak.

In Fig. 6(a) an oscilloscope trace of V_{ac} is shown. The sample used here is an nonimplanted N-type silicon from the same ingot of sample S_1 but no intention was made for special surface treatments and surface is at dark. Therefore, surface traps are higher and can be observed by the difference V_p-V_{pf}. In Fig. 6(b) the same sample of Fig. 6(a) is used but the surface is illuminated by white light through $LiNbO_3$. Application of light will fill up all the

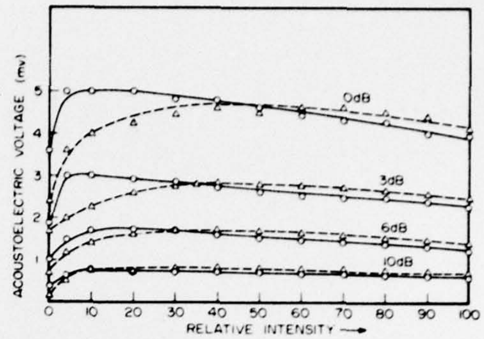

Fig. 5 Acoustoelectric voltage as a function of relative intensity for sample S_3. The numbers in dB in each curve denote the attenuation of rf from 15 volts peak-to-peak.

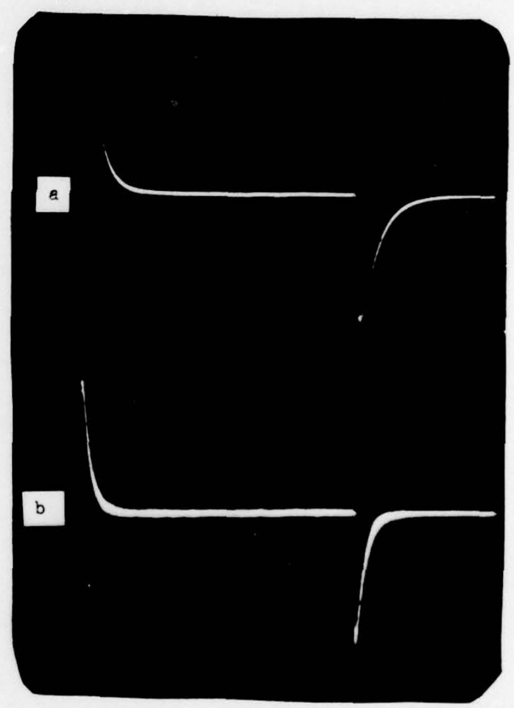

Fig. 6 V_{ac} for a nonimplanted N-type silicon from the same ingot of sample S_1 when surface, intentionally, is not clean. (a) Surface is at dark; (b) Surface is illuminated by light of moderate intensity. Horizontal scale is 0.5 ms/div.; vertical scale is 2 mv/div.

surface traps and it can be observed by noting V_p=V_{pf}.

Figure 7 is a multiexposure oscilloscope picture taken from the V_{ac} waveform for sample S_1 where successive traces correspond to increasing light intensity and they are horizontally shifted for clarity. Identical numbers correspond to one trace when the peaks in the upper part and lower part of the trace are V_p and V_{pf} respectively, and the first trace is V_{ac} at dark. In this figure the low density of surface states can be observed by noting the difference V_p-V_{pf} is very small at dark and V_d will tend to zero at low level light.

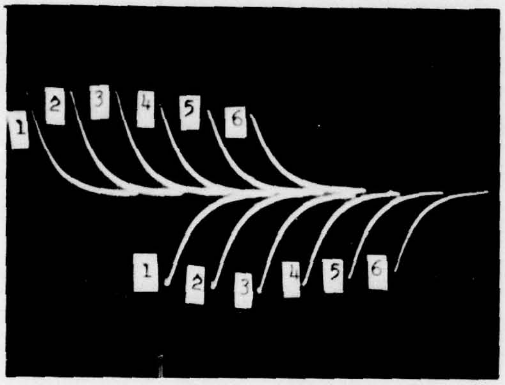

Fig. 7 V_{ac} for sample S_1 where successive traces correspond to increasing light intensity and they are horizontally shifted for clarity. Horizontal scale is 0.5 ms/div.; vertical scale is 5 mv/div.

Figure 8 is another multiexposure oscilloscope picture taken from sample S_2. The variation of V_p, V_{pf} and V_d can be observed as the light intensity increases with successive traces.

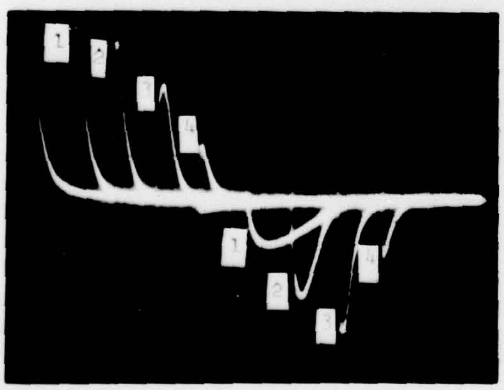

Fig. 8 V_{ac} for sample S_2 where successive traces correspond to increasing light intensity and they are horizontally shifted for clarity. Horizontal scale is 0.5 ms/div.; vertical scale is 2 mv/div.

We note qualitative differences between the data on the three samples. In S_1 (Figs. 3 and 7), V_p remains constant at low value of relative intensity and decreases as relative intensity increases. The difference between V_p and V_{pf} is very small, and it is practically zero when the rf pulse to the SAW transducer was attenuated more than 6 dB. However, in the implanted samples S_2 and S_3 (Figs. 4, 5, and 8), V_p increases at low values of relative intensity and goes to a maximum and then decreases as relative intensity increases. V_{pf} shows the same variation and the difference between V_p and V_{pf} is initially vary large and decreases to zero and then changes the sign as the relative intensity increases. This difference of V_p-V_{pf} could be observed for S_2 and S_3 even when the rf pulse is attenuated more than 10 dB.

Figure 9 shows variation of four related time constants of acoustoelectric voltage for sample S_2, as a function of relative intensity. Time constants τ_1 and

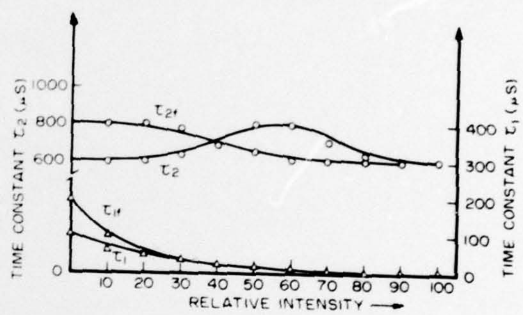

Fig. 9 Variation of four related time constants of V_{ac} as a function of relative intensity.

τ_{1f} are considerably small as compared with τ_2 and τ_{2f}. τ_1 and τ_{1f} both are initially large and then eventually, decrease to a value around 20 μs. Time constant τ_2 has a peak value around 50 to 60% maximum available intensity and time constant τ_{2f} is high and remains constant at low intensity and then reduces as relative intensity increases and remains constant at high intensity. The four time constants of acoustoelectric waveforms were measured as a function of relative intensity for sample S_2 and they are plotted in Fig. 9.

To correlate acoustoelectric voltage with delay line attenuation and qualitatively explain some of the observed phenomena in V_{ac} waveforms, terminal "1" was fed with a (10 volt P.P.) rf pulse and delayed output was observed from terminal "2". The data of attenuation as a function of relative intensity are plotted for three samples S_1, S_2 and S_3 and it is shown in Fig. 10.

Discussion

Since sample S_1, unimplanted sample, had been prepared with special surface cleaning treatment, we expected a low density of surface states and as a result, in all the observed waveforms the portion of V_{ac} being screened out by traps is very small and the difference V_d is only pronounced at low values of incident intensity and moderate acoustic powers (10 to 15 volts P.P.). These results are shown in Fig. 3.

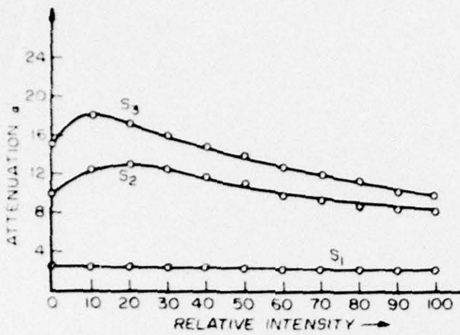

Fig. 10 Attenuation as a function of relative intensity for all three samples.

The decrease of V_{ac} when relative intensity increases is the result of $1/\sigma$ dependent on acoustoelectric voltage and slight attenuation of delayed output vs. relative intensity (see Fig. 10). A multiexposure oscilloscope picture of Fig. 7 covers some part of the data plotted in Fig. 3. Here we can observe that the surface state density is very small. However, in Fig. 6 the same silicon sample shows a high density of surface states for the reason we indicated before.

Sample S_2 consists partially of a compensated region due to the implanted layer and has a calculated value of $u_B \approx 4$ (bulk potential averaged in Debye length) where the N-type substrate has an original u_B = 10 which is constant through the bulk. The sample is slightly N-type at the surface and as the layers are deeper inside the surface we have first an inversion to P-type and then second inversion back to the original N-type. This can be mathematically interpreted as follows: around 3000 $\AA$ from the surface intrinsic Fermi level starts to bend upward crossing the Fermi level at 2000 $\AA$ and passes its maximum at 1200 $\AA$ and then decreases, crossing one more time the Fermi level at 400 $\AA$ and reaches the surface slightly below the Fermi level. In this bending, quasi-intrinsic Fermi level always remains above the intrinsic Fermi level, therefore, positive charges are accumulated within the depth of 3000 $\AA$ from the surface which has a peak value at 1200 $\AA$ and reduces near the surface. For the depth of 400 $\AA$, the original N-type is depleted and deeper inside the surface is inverted

Figure 4 shows the results of data taken on sample S_2. The initial rise of V_p is due to the increase of attenuation α, as a function of relative intensity[10] (see Fig. 10). After the attenuation passes the peak, V_p tends to decrease which is the same effect of $1/\sigma$ dependent on acoustoelectric voltage. The difference voltage (between V_p-V_{pf})V_d is positive at low level light and as the relative intensity increases it becomes zero and eventually changes the sign and becomes negative. It should be indicated that the negative value of V_d at high intensity illumination has been observed only for implanted silicon surfaces. For non-implanted silicon samples, at low intensity V_d is positive and at moderate intensity levels (40% to 50% maximum available light intensity) it becomes zero and then remains zero at higher intensities.

To explain qualitatively why V_d being negative for ion implanted samples at high levels of light intensity we note that Fermi level tends to move downwards as relative intensity increases and so inversion layer moves closer to the surface. This mathematical interpretation indicates a parallel resistor should bridge from the mass of inversion layer to the gound terminal resulting in a limitation for terminal capacitance being charged initially to the maximum available voltage. Therefore, the crossing point of the solid line and dashed line in Figures 4 and 5 can be used as a measure of depth of depletion and inversion layer, deviation of Fermi energy from intrinsic value, surface conductivity, and the location of the implant and the shape of its distribution. Figure 5 shows the results of data taken on sample S_3. The variation of V_{ac} as a function of relative intensity has a similar shape as the one for sample S_2. The crossing points of solid and dashed lines are shifted towards higher intensities indicating depletion layers are deeper inside the surface. This is true because sample S_3 has an implant distribution, peaked at 3200 $\AA$ as compared with 1200 $\AA$ of sample S_2.

The results on time constants of acoustoelectric waveforms, plotted for implanted sample S_2 in Fig. 9, are very difficult to interpret at this time. For qualitative explanation of V_{ac} time constants, it is necessary to use a light of single frequency with variable intensity. The wavelength response of acoustoelectric voltage at different intensities gives us a reasonable enough knowledge to measure location and kind of traps in surface and its vicinity and their capture and relaxation times. This work is in progress.

In conclusion, the transient shape of acoustoelectric voltage V_{ac} produced by a surface acoustic wave closely coupled to a silicon surface with ion implanted layers near the surface has been shown to be dependent on the implanted ion distribution. The interaction between silicon samples and SAW is controlled by surface illumination through the $LiNbO_3$, the results presented here demonstrated that acoustoelectric voltage V_{ac} is very sensitive to light and it can be used for a nondestructive testing of implanted surface, the depth of depletion and inversion layer, type of semiconductor surface (N-type or P-type) and distribution of implant can qualitatively be studied by this method.

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